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6. AUTHOR(S)

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13. ABSTRACT (Maximum 200 words)

The supported research sought to apply interference lithography technology as a tool for metrology in the sub-100 nm critical dimension (CD) linewidth regime. Semiconductor industry roadmaps show CDs shrinking to under 35 nm within 15 years. This requires mask image placement metrology accuracy of 2 nm by 2014. There are currently no industry length-scale calibration standards at any level of accuracy that may be used to ensure metrology tool accuracy. Instead, the industry relies on various self-referencing schemes which are inaccurate, expensive, time consuming, and ineffective. MIT developed technology to produce image placement metrology standards that achieved sub-5 nm accuracy by the end of this Grant. MIT developed a new tool, called scanning-beam interference lithography (SBIL), which is used to pattern super-accurate grids that will serve as length scale standards. MIT built and tested Phase 1 of the SBIL tool, proving the concept, and then went on to design, build, and test Phase 2 of the tool. The tool was successfully used to pattern 300 mm wafers with 400 nm period gratings which has repeatability of under 3 nanometers.

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**(Continuation Sheet)**

## Scientific Personnel

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## Short Statement of Program Goals

The supported research sought to apply interference lithography technology as a tool for metrology in the sub-100 nm (nanometer) critical dimension (CD) linewidth regime. Semiconductor industry roadmaps show CDs shrinking to under 35 nm within 15 years. This requires mask image placement metrology accuracy of 9 2 nm by 2014. There are currently no industry length-scale calibration standards at any level of accuracy that may be used to ensure metrology tool accuracy. Instead, the industry relies on various self-referencing schemes which are inaccurate, expensive, time consuming, and ineffective. MIT developed technology to produce image placement metrology standards that achieved under 5 nm accuracy by the end of this Grant. Many other industrial and military electronics applications would issue from such super-accurate gratings, including encoders and integrated optoelectronic devices.

## Accomplishments

MIT has completed the construction and testing of a novel lithography tool called the Nanoruler, which is capable of writing and reading large gratings with unprecedented accuracy. MIT have demonstrated the writing and reading of gratings with a phase stability and repeatability of well under 3 nm, 3 .

The Nanoruler utilizes the principle of scanning-beam interference lithography (SBIL), which involves the interference of small beams to create a grating “image,” and then scanning a substrate under the image using a high-performance air-bearing stage. Stage and fringe phase errors are measured using heterodyne digital phase meters and locked out by use of acousto-optic phase shifters driven by a digital frequency synthesizer and high-speed digital controls. The Nanoruler is housed in a special environmental chamber to ensure the extremely tight environmental stability required to achieve nanometer fringe stability. Typical system positional stability during a period of 1 min has been demonstrated to be 2.1 nm, 3 . The Nanoruler is capable of patterning gratings and grids with periods down to 200 nm on 300 mm-diameter substrates.

One of the goals of the Nanoruler was to demonstrate that large, nano-accuracy gratings can be used as optical encoders to replace interferometers in lithography and metrology stages, thereby wringing out a large source of CD and overlay errors. Stage error is an important component of overlay and CD budgets. In reading

mode, the Nanoruler is designed to read the position and map the phase of gratings written by itself or other tools. In this mode, it thus performs essentially as an optical encoder with a precision of ~2 nm.

Improving stage error is becoming increasingly important as linewidths continue to shrink. A 2 nm stage position error is called for at the 30 nm node. Improved overlay and CD control are critically important for planar multilevel processing as the industry follows the high-volume manufacturing roadmap. However, it is of equal, if not greater importance for the low volume, high performance products of interest in defense electronics. Essentially handcrafted fixes to overlay and CD problems are becoming increasingly common as linewidths and k-factors shrink. These errors are increasingly driven by tool, pattern and process-dependant issues. While these costs can perhaps be bourn during high-volume production of consumer chips, during low-volume production by direct-write lithography of high-performance nanometer-sized devices, problems with CD and overlay control become increasingly expensive and time consuming to rectify.

**Manuscripts submitted, but not yet published.**

R121. “Effects of varying incident angle on the contrast of the fringe metrology using a Fresnel zone plate," C. Joo, G.S. Pati, C.G. Chen, P.T. Konkola, R.K. Heilmann and M.L. Schattenburg, *Proc. of the Seventeenth Annual Meeting of the American Society for Precision Engineering* (ASPE, Raleigh, NC) (*submitted August 2002*).

**Papers published in peer-reviewed journals.**

R79. “Sub-100 nm metrology using interferometrically produced fiducials,” M.L. Schattenburg, C. Chen, P.N. Everett, J. Ferrera, P. Konkola and H.I. Smith, *J. Vac. Sci. Technol. B* **17**, 2692-2697 (1999).

R80. “Fabrication of patterned media for high density magnetic storage,” C.A. Ross, H.I. Smith, T. Savas, M.L. Schattenburg, M. Farhoud, M. Hwang, M. Walsh, M.C. Abraham and R.J. Ram, *J. Vac. Sci. Technol. B* **17**, 3168-3176 (1999); also *Microelectronic Engineering* **53**, 67 (2000) (*abstract only*).

R81. “A Holographic Phase-Shifting Interferometer Technique to Measure In-Plane Distortion,” M.H. Lim, J. Ferrera, K.P. Pipe and H.I. Smith, *J. Vac. Sci. Technol. B* **17**, 2703-2706 (1999).

R89. “Relativistic corrections in displacement measuring interferometry,” R.K. Heilmann, P.T. Konkola, C.G. Chen and M.L. Schattenburg, *J. Vac. Sci. Technol. B* **18**, 3277-3281 (2000). (*CSR reprint 00-34*)

R90. “Beam steering system and spatial filtering applied to interference lithography,” P. Konkola, C.G. Chen, R.K. Heilmann and M.L. Schattenburg, *J. Vac. Sci. Technol. B* **18**, 3282-3286 (2000). (*CSR reprint 00-47*)

R100. “Image metrology and system controls for scanning beam interference lithography,” C.G. Chen, P.T. Konkola, R.K. Heilmann, G.S. Pati and M.L. Schattenburg, *J. Vacuum Sci. Technol. B* **19**, 2335-2341 (2001). (*CSR Reprint 01-64*)

R101. “Digital heterodyne interference fringe control system,” R.K. Heilmann, C.G. Chen, P.T. Konkola, G.S. Pati and M.L. Schattenburg, *J. Vacuum Sci. Technol. B* **19**, 2342-2346 (2001). (*CSR Reprint 01-53*)

R110. “Analysis of vector Gaussian beam propagation and the validity of paraxial and spherical approximations,” C.G. Chen, P.T. Konkola, J. Ferrera, R.K. Heilmann and M.L. Schattenburg, *J. Optical Society of America A* **19**, 404-412 (2002). (*CSR Reprint 00-48*)

R111. “Beam alignment and wavefront metrology for scanning beam interference lithography,” C.G. Chen, R.K. Heilmann, C. Joo, P.T. Konkola, G.S. Pati and M.L. Schattenburg, *J. Vac. Sci. Technol. B* **20**, 3071-3074 (2002). (*CSR Reprint 02-34*)

R112. “Nanometer-accurate fringe metrology using a Fresnel zone plate,” C. Joo, G.S. Pati, C.G. Chen, P.T. Konkola, R.K. Heilmann, M.L. Schattenburg, A. Liddle and E.H. Anderson, *J. Vac. Sci. Technol. B* **20**, 3075-3079 (2002). (*CSR Reprint 02-35*)

R113. “A generalized scanning beam interference lithography system for patterning gratings with variable period progressions,” G.S. Pati, R.K. Heilmann, P.T. Konkola, C. Joo, C.G. Chen, E. Murphy and M.L. Schattenburg, *J. Vac. Sci. Technol. B* **20**, 2617-2621 (2002). (*CSR Reprint 02-35*)

R123. “Spatial phase locking with shaped beam lithography,” J.G. Hartley, T.R. Groves, H.I. Smith, M.K.

Mondol, J.G. Goodberlet, M.L. Schattenburg, J. Ferrera and A. Bernshteyn, *Rev. Sci. Instrum.* **74**, 1377-1379 (2003). (*CSR Reprint 01-86*)

## Papers published in conference proceedings.

R103. “Scanning beam interference lithography,” P.T. Konkola, C.G. Chen, R.K. Heilmann, G. Pati and M.L. Schattenburg, *Proceedings of the Sixteenth Annual Meeting of the American Society for Precision Engineering* (American Society for Precision Engineering, Raleigh, NC), 15-18 (2001). (*CSR Reprint 01-102*)

R105. “A novel sub-microradian beam diagnostic and alignment system,” C.G. Chen, R.K. Heilmann, P.T. Konkola, G.S. Pati and M.L. Schattenburg, *Proceedings of the Sixteenth Annual Meeting of the American Society for Precision Engineering* (American Society for Precision Engineering, Raleigh, NC), 216-219 (2001). (*CSR Reprint 01-104*)

R106. “Field emitter arrays for low voltage applications with sub 100 nm apertures and 200 nm period,” D.G. Pflug, M.L. Schattenburg, H.I. Smith and A.I. Akinwande, *Technical Digest, 2001 IEEE International Electron Device Meeting* (*IEDM*), (IEEE, Piscataway, NJ), 179-182 (2001). (*CSR Reprint 01-87*)

R107. “The critical role of metrology in nanotechnology,” M.L. Schattenburg and H.I. Smith, *Proc. SPIE* **4608**, *Nanostructure Science, Metrology, and Technology*, eds. M.C. Peckerar and M.T. Postek, Jr. (SPIE, Bellingham, WA), 116-124 (2001). (*CSR Reprint 01-105*)

R108. “Progress towards a general grating patterning technology using phase-locked scanning beams,” M.L. Schattenburg, C.G. Chen, R.K. Heilmann, P.T. Konkola and G.S. Pati, *Proc. SPIE* **4485**, *Optical Spectroscopic Techniques and Instrumentation for Atmospheric and Space Research IV*, eds. A.M. Larar and M.G. Mlynczak, 378-384 (2002). (*CSR Reprint 01-83*)

R122. “Nanometer-accurate grating fabrication with scanning beam interference lithography,” C.G. Chen, P.T. Konkola, R.K. Heilmann, C. Joo and M.L. Schattenburg, *Proc. SPIE* **4936**, *Nano- and Microtechnology: Materials, Processes, Packaging, and Systems* (SPIE, Bellingham, WA), ed. D.K. Sood, 126-134 (2003).

## Student Master’s Thesis

Carl Gang Chen, *Microcomb Fabrication for High Accuracy Foil X-ray Telescope Assembly and Vector Gaussian Beam Modeling*, M.S.E.E.C.S. 2000.

## Student Ph.D. Thesis

Dr. Paul Thomas Konkola, *Design and Analysis of a Scanning Beam Interference Lithography System for Patterning Gratings with Nanometer-Level Distortion*, Ph.D. Thesis, Department of Mechanical Engineering, April 2003.

Dr. Carl Gang Chen, *Beam Alignment and Image Metrology for Scanning Beam Interference Lithography – Fabricating Gratings with Nanometer Phase Accuracy*, Ph.D. Thesis, Department of Electrical Engineering and Computer Science, April 2003.

## Patents

“A method for interference lithography utilizing phase-locked scanning beams,” M. L. Schattenburg and P. N. Everett, U. S. Patent (*pending*).

“Improved method for interferometric displacement measurement,” R. K. Heilmann and M. L. Schattenburg, U. S. Patent (*pending*).

## Technology Transfer

We have had the significant technical contacts with the following companies, including factory visits, phone calls, and meetings. These contacts specifically concerned MIT's technology in metrology, funded by this ARO contract.

Intel
IBM
Ultratech Corp.
SVG Lithography
Applied Materials (Etec)
Motorola
Texas Instruments